

**DEVELOPMENT OF HIGH RESOLUTION HARD X-RAY TELESCOPE  
WITH MULTILAYER COATINGS**

NASA Grant No. NAG5-5354

Progress Report No. 2

For Period 1 April 2003 through 31 March 2004

Principal Investigator  
Dr. Paul Gorenstein

February 2004

Prepared for:

National Aeronautics and Space Administration  
Goddard space Flight Center  
Wallops Island, VA 23337

Smithsonian Institution  
Astrophysical Observatory  
Cambridge, Massachusetts 02138

<p>The Smithsonian Astrophysical Observatory is a member of the Harvard-Smithsonian Center for Astrophysics</p>
---

The NASA Technical Officer for this Grant is John C. Brinton, NASA/Goddard Space Flight Center, Wallops Island, VA 23337

## **1. INTRODUCTION**

### **1.1 Program Objectives**

The major objective of this program is the development of a focusing hard X-ray telescope with moderately high angular resolution, i.e. comparable to the telescopes of XMM-Newton. The key ingredients of the telescope are a depth graded multilayer coatings and electroformed nickel substrates that are considerably lighter weight than those of previous missions such as XMM-Newton, which have had conventional single metal layer reflective coatings and have operated at much lower energy X-rays. The ultimate target mission for this technology is the Hard X-Ray Telescope (HXT) of the Constellation X-Ray Mission. However, it is applicable to potential SMEX and MIDEX programs as well.

The distinctive feature of this approach compared to other hard X-ray telescope programs is that superior angular resolution is expected thanks to the structural integrity of the substrates. They are thin walled complete cylinders of revolution with a Wolter Type 1 figure; the front half is a parabola, the rear half a hyperbola.

### **1.2 Collaborations**

We are collaborating with two other groups that receive funding independently, one at the Brera Observatory in Italy and the other at the National Space Science and Technology Center, which was spun off the Marshall Space Flight Center in Huntsville, Alabama. We rely upon our collaborators for substrate production but we participate fully in evaluating and identifying methods for improving the quality and lowering the mass of the substrates. SAO provides all the reflective coatings.

## **2. ACCOMPLISHMENTS OF THE PAST YEAR**

### **2.1 Improvements to the deposition facility.**

Construction of the multilayer deposition facility was completed the previous year but its operation was improved during the past year. A collimator was added to reduce the angular spread of the sputtering beam to a narrower region centered at normal incidence. The result was smoother coatings with higher reflection efficiency. However, the presence of the collimator resulted in a slower rate of deposition at the same power level. This was not desirable because it increases the time that the substrate is heated, exacerbating the mismatch in the coefficient of thermal expansion between tungsten silicon coatings and the nickel substrate. Further experimentation reveal that we could obtain almost the same quality coatings by collimating only in the horizontal plane. We were also able to improve the quality by maintaining the distance between the sputtering gun and the substrate within a narrow ranges around 3 cm. However, that is not possible for the full range of shell diameters. Therefore we will sputter at a distance of exactly 3 cm when possible and collimate in the horizontal dimension when it is not.

### **2.2 Coating electroformed mirror shells with multilayers.**

An electroformed nickel shell was delivered in April 2003 by our collaborators at the Brera Observatory in Italy to SAO. The mirror shell arrived with a gold coating on the interior reflecting surface, which is present to expedite its release from the forming mandrel. The presence of the gold coating while unavoidable is problematic. By virtue of its being a release agent the multilayer coating is not expected to adhere to it as well as it would to the bare nickel. A series of depositions of a W/Si multilayer were carried out along several different regions of azimuth. In this manner, a single shell could be used for multiple coating deposition experiments.

Our first coatings were applied before the introduction of the collimator and before the optimum distance was determined. The quality of the coating was fair. The model interface roughness between layers was about 0.73 nm rms, which is acceptable for X-rays with energy lower than 45 keV. Following some experimentation with the deposition rate and temperature the X-ray reflectivity of subsequent coatings were superior. However, we were not able to obtain as good X-ray reflectivity with the mirror shell as we were with silicon wafer witness samples. Experimentation continued with two more shells delivered by Brera.

### 2.3 Adhesion of coating

The first shell was returned to Brera for optical testing. Several months later they observed that one of the coatings delaminated from the shell. This raised concern about adhesion to gold. We performed a series of adhesion experiments with samples cut from an older gold coated shell (one of the spares from the construction of the SWIFT mirror). Two samples were coated with a W/Si multilayer directly and we applied a thin coating of chromium to the other pair before depositing the multilayer. Chromium is known to adhere well to most materials so the hope was that as an intermediary it would bond the W/Si multilayer more firmly to the gold. The difference between the two members of each pair was that the Si was deposited first in one and W first in the other. Silicon was the first element deposited of the multilayer coating that separated from the gold. The expectation was that W would adhere more firmly to the gold than Si.

Tape pull separation tests were carried out on all four samples. None of the samples yielded. Several months later the coatings are still in tact. Therefore, we have not identified the cause for the coating separating from the shell section. It is possible that the shell section had an non-visible contamination. The samples will be thermally cycled between the cold and hot survival temperatures of a typical space mission. The differential thermal expansion between the coating and shell will result in stress upon the coating and will be a further test of the adhesion.

### 2.4 Assessment of distortion caused by stress

Certain coating compositions are known to exert stress upon the substrate. The stress can be a result of a difference in the coefficient of thermal expansion between the coating and the substrate. The temperature rises to about 40 C during the sputtering process and will cool ultimately to room temperature. Nickel has a relatively high

coefficient of thermal expansion while our preferred coating of W/Si has a low coefficient. Therefore we expect that there will be some residual stress in the coated shell. However, because the shell is a complete cylinder of revolution the stress may well balance. Our collaborators at the Marshall Space Flight Center provided several 100 micron thick electroformed nickel shell about 50 cm long for testing. The figure of the shell was measured at MSFC before and after the deposition of the coating. We coated the shell with a W/Si multilayer and returned it to MSFC where their profilers were able to compare the before and after figure. The conclusion is that happily the distortion in the mirror shell that is induced by stress in the coating is not significant. Another multilayer coating material combination that we are considering for future X-ray telescopes, Pt/C, matches the coefficient of thermal expansion of nickel rather well and is not expected to exert significant stress when it cools to room temperature.

## 2.5 Angular resolution of thin shell

The Hard X-ray Telescope of the Constellation X-ray Mission, the main target of this program, has rather demanding mass constraints. For compatibility we must reduce the mass of an electroformed telescope by making walls that are a factor of three thinner than the electroformed telescopes of XMM-Newton and SWIFT. This must be done without too much loss of angular resolution. The process of removing the shell from the mandrel produces the largest stress to which the replica shell is ever subjected. Consequently the largest distortion occurs during separation. We surveyed the literature and posed questions to industry in an effort to identify a separation agent that is more effective gold, i.e. requires less force. We were not successful in finding one.

The Media Lario company in Italy, had identified and put into use a new type of nickel alloy that has more stiffness than the replica shells they fabricated for SWIFT<sup>1</sup> and XMM-Newton a decade ago. With this new alloy they electroformed a new replica shell from an existing SWIFT mandrel and delivered it to our Italian collaborators at the Brera Observatory. The thickness was a factor of six less than the corresponding shell in the SWIFT X-ray mirrors and a factor of three less than similar XMM-Newton mirrors.

The imaging properties of the mirror shell were tested in visible light and X-rays. In both wavelength regimes the angular resolution of the mirror shell was 25 arcseconds. That will satisfy our requirements for the Con-X HXT. Because the major contribution to the error is the figure fidelity of the individual concentric mirror shells rather than errors in their alignment, the resolution of this single shell is representative of what we can expect from the entire mirror assembly.

The surface roughness of the mandrel is too large to allow the production of replica shells that are suitable substrates for multilayer coatings.

---

<sup>1</sup> SWIFT is scheduled for launch in 2004 but its telescope was constructed about 10 years ago for a payload known as "JET-X" which was part of the payload of the Russian spacecraft known as *Spectrum-X-Gamma*. That mission was suspended following the demise of the Soviet Union. The SWIFT mirror is a spare for JET-X.

### 3. STATEMENT OF WORK FOR FY/05

The following describes what we plan to do during the third year of this grant.

A. In collaboration with our Italian colleagues construct and coat a short shell from a new, highly polished mandrel whose surface roughness is low enough to allow the production of replicas that can serve as a base for multilayer coatings.

B. Test the replica in a broad spectrum X-ray beam up to 40 keV. The X-ray facility for this test series and the one referred to below will be the Panter facility owned by the Max Planck Institute for Extraterrestrial Physics (MPE) in Garching (Munich) Germany. They will make it available to us at no cost to this program

C. Design and test at the MPE Panter facility a full length replica shell, 42.6 cm, electroformed from another new mandrel that is currently being polished.

D. Analyze the data from both tests.

E. Add new features to the X-ray sputtering facility that increase its versatility.

1. Add a radial movement capability to the cathodes so that we can maintain the optimum separation between each of two cathodes and the replica through a range 22 to 55 cm in replica diameter.

2. Redesign and rebuild shutters for the cathodes that enable us to interrupt or terminate the deposition process as needed.

3. Install chromium target. If required a single chromium layer will improve the adhesion of multilayer coatings to the gold-coated replicas.

F. Add an infrared thermometer system to monitor the temperature increase of the substrate during deposition. This will allow us to implement and evaluate new strategies for minimizing the temperature rise.

G. Continue stress and adhesion studies.

#### 4. PAPERS ACCEPTED FOR PUBLICATION IN 2003

Gorenstein, P. *Role of diffractive and refractive optics in x-ray astronomy*, **SPIE 5168** (In Press), 2004.

Skinner, G and Gorenstein, P. *Black Holes, Fleas and Microlithography*, **Nature 426**, 245, 2003.

S.Romaine, S. Basso, R.J.Bruni, O.Citterio, D.Engelhaupte, M.Ghigo, P.Gorenstein, M.Gubarev, F. Mazzoleni, S.L.O'Dell, G.Pareschi, G.Parodi, B.D.Ramsey and C.Speegle *Development of a Prototype Nickel Optic for the Constellation-X Hard X-Ray Telescope*, **SPIE 5168** (In Press), 2004